Paper.
#77

EMI Performance of the AIRS Cooler and Electronics

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ABSTRACT

The TRW pulse tube cryocooler for JPL's Atmospheric Infrared Sounder (AIRS) instrument is required to meet stringent requirements for radiated electric and magnetic fields, conducted emissions on the input power bus, and electromagnetic susceptibility. To meet the radiated magnetic field requirements, special mu-metal shields were designed, fabricated, and fitted to the cooler following an extensive period of magnetic testing with mock-up cooler hardware. Excessive magnetic fields is a generic issue with linear-motor cryocoolers, as is excessive levels of input ripple current. Solving the ripple current issue required the addition of a dedicated ripple filter as part of the spacecraft power system.

As one of the first cryocoolers with flight electronics available for testing, the AIRS cooler offered an important opportunity to measure and understand these important issues. This paper describes the development of the magnetic shields to bring the AC magnetic fields of the AIRS cooler within the requirements of MIL-STD-461C, includes before and after data on the achieved field levels, and presents extensive data on the suite of EMI characteristics of the AIRS cooler with its flight electronics.

Because of its importance, levels of input ripple current are presented as a function of compressor input power to allow future applications to judge the ripple-current compatibility with specific power system capabilities and to serve as data for scoping the design of ripple suppression hardware.

INTRODUCTION

Instrument Overview

The objective of the Atmospheric Infrared Sounder (AIRS) instrument is to make precision measurements of atmospheric air temperature over the surface of the Earth as a function of elevation. It is scheduled to be flown on NASA's Earth Observing System PM platform in the year 2000.

The technical foundation of the AIRS instrument is a cryogenically cooled infrared spectrometer that uses a pair of TRW 55K pulse tube cryocoolers[1-4] to cool the HgCdTe focal plane to 58 K. The spectrometer operates over a wavelength range from visible through 15.4 μm, and places demanding requirements on the EMI performance of the cryocooler and its electronics.

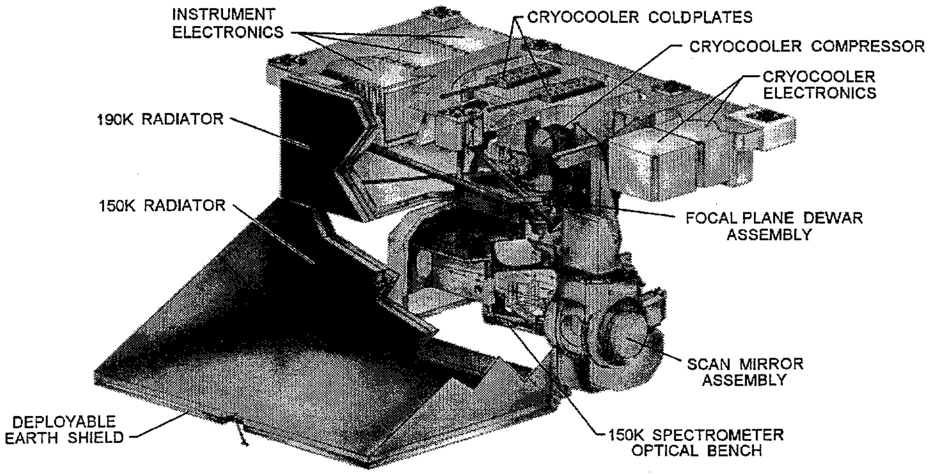


Figure 1. Overall AIRS instrument showing proximity of instrument electronics to the cryocoolers.

Figure 1 illustrates the overall instrument and highlights the key assemblies and the close proximity between the cryocoolers and the sensitive instrument electronics. Physically, the instrument is approximately 1.4 m x 1.0 m x 0.8 m in size, with a mass of 150 kg, and an input power of 220 watts.

Early in the design of the AIRS instrument, two key decisions of design philosophy were established that served as fundamental ground rules for the approach to meeting the cryocooler EMI design requirements. These included: 1) cooler drive fixed at 44.625 Hz, synchronized to the instrument electronics—to minimize pickup of asynchronous EMI noise (or vibration) from the cryocooler, and 2) cooler drive electronics fully isolated (dc-dc) from input power bus

Because the required cryocooler EMI performance was better that any existing cryocooler at the beginning of the AIRS development effort, the AIRS Project established a collaborative in-house/contractor teaming approach to achieve the necessary cryocooler EMI performance. This integrated-product-team approach involved the cryocooler developer (TRW Space & Technology Division of Redondo Beach, CA), who took primary responsibility for the cryocooler's EMI design, the AIRS instrument developer (Lockheed Martin IR Imaging Systems of Lexington, MA), who took primary responsibility for the instrument compatibility, and JPL, who took primary responsibility for the AC magnetic shield and supplemental EMI filter development, EMI acceptance testing, and spacecraft interface negotiations.

The remainder of the paper details the EMI requirements on the AIRS cryocoolers, summarizes the overall EMI design approach undertaken including development tests, and describes the final results of the extensive series of Qualification Acceptance tests conducted on the flight cryocooler (PFM) units.

AIRS CRYOCOOLER RADIATED AND CONDUCTED EMISSIONS

The Electromagnetic Interference (EMI) design requirements on the AIRS cryocoolers are fundamentally interface requirements associated with assuring electrical operational compatibility between the AIRS cryocoolers and their electrical neighbors; these neighbors include the very sensitive electronics in close proximity to the coolers within the AIRS instrument itself (particularly the electronics associated with the focal plane readout), the electronics associated with neighboring instruments and the spacecraft itself, and the spacecraft power system that provides the 28 Vdc bus power to the cryocoolers.

The EMI requirements associated with these interfaces fall into three areas, which, in the case of AIRS, are tailored from the popular MIL-STD-461C baseline:[5]

- Radiated magnetic field emissions (30 Hz to 50 kHz)
- Radiated electric field emissions (14 kHz to 18 GHz)
- Conducted AC currents on the 28 Vdc power bus (30 Hz to 50 MHz)

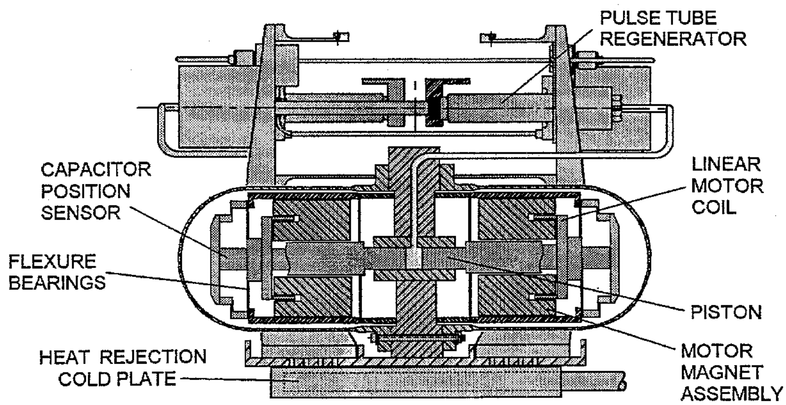


Figure 2. Cryocooler system showing internal compressor operational elements.

Radiated Magnetic Field Emissions

In interpreting the radiated magnetic field requirement with respect to the AIRS compressor it is useful to first understand the fundamental electromagnetic structure of the cryocooler. The AIRS compressor, shown schematically in Fig. 2, is a mechanically resonant system with two pistons acting into a common compression space. Each flexure-suspended piston assembly operates much like a loudspeaker, whereby it is driven via a moving coil in a permanent magnetic field. Piston motion and gas compression is generated by simultaneously applying an alternating current through the coils of the two piston assemblies at the drive frequency of 44.625 Hz. This frequency was chosen to optimize the overall performance of the AIRS instrument and cooler, and the compressor was then tuned to be near mechanical resonance at this frequency to maximize the drive motor efficiency.

Compressor AC Magnetic Emissions. Two sets of AC magnetic field measurements are typically made to quantify cryocooler AC magnetic field emissions: 1) at a 7-cm distance, corresponding to the MIL-STD-461C RE01 test specification[5], and 2) at a 1-m distance, corresponding to a MIL-STD-462 RE04 test method. The measurements are made using a standardized 37-turn loop antenna positioned the required distance from the outer surface of the compressor or electronics box.

Figure 3 summarizes the RE01 performance of a number of representative Oxford-type space cryocoolers, not including AIRS, which use the same fundamental piston-drive approach as

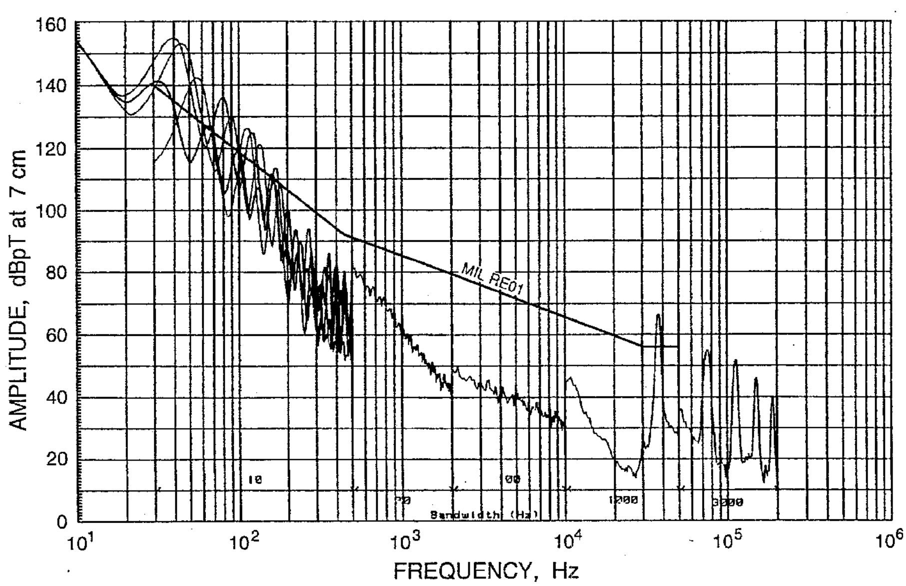


Figure 3. AC magnetic field emissions measured for a variety of Oxford-type space cryocoolers (versus MIL-STD-461C RE01 requirements).

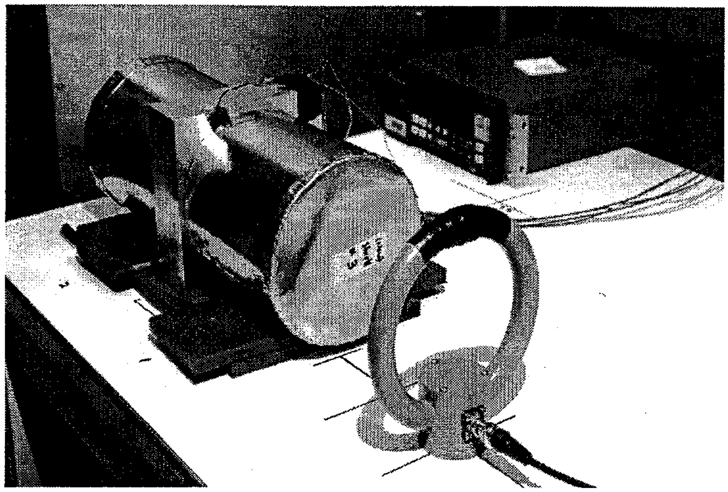
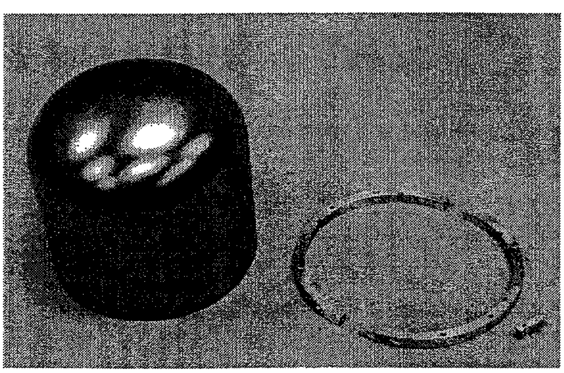


Figure 4. Magnetic shielding studies used this "magnetic mock-up" of the AIRS compressor with various shield materials, thicknesses and configurations.

the AIRS cooler.[6] The data are plotted in decibels above 1 pT; the breaks in the measured data are due to changes in the amplifier gain and spectrum analyzer bandwidth settings. Note that the radiated magnetic field emission levels for the fundamental drive frequency are typically above the MIL-STD-461C specification. After the first three or four harmonics, the levels rapidly drop and reach background ambient levels above 1 kHz. Radiated magnetic emissions observed above 10 kHz are typically emissions at the harmonics of the switching power supply drive frequency.

Given the inability of most previous space coolers to meet the MIL-STD-461C RE01 requirement, the AIRS cooler was designed from the beginning to incorporate magnetic shielding. Originally, mu-metal shields were to be incorporated around each compressor motor internal to the compressor pressure housing. However, early measurements of the shields' effectiveness showed that the shields were saturating from being too close to the magnetic source and were providing shielding levels below 5 dB. A number of magnetic shielding studies were next run using various configurations of CO-NETIC AA[7] and Moly Permalloy[8] shields on a magnetic mock-up of the AIRS cooler as shown in Fig. 4. These tests showed that field reductions of the order of 20 dB could be achieved with external shields, and still meet the tight volume and mass restrictions imposed by integration constraints within the AIRS instrument. The final shield design, shown in Fig. 5, utilizes 0.5-mm (0.020") thick shields hydroformed from Moly Permalloy



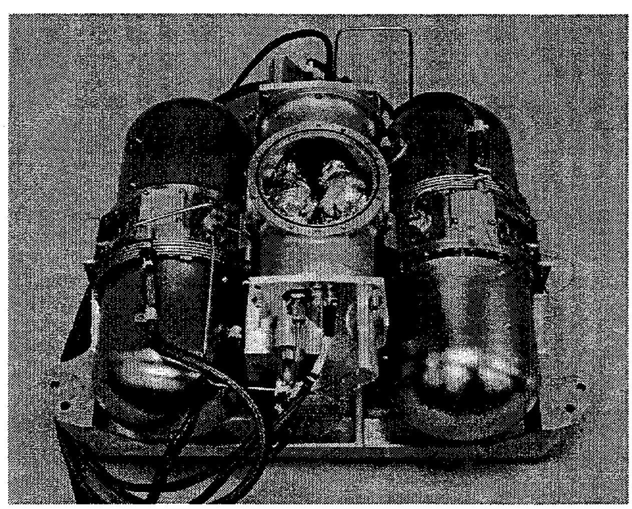


Figure 5. Flight magnetic shield and one of two mounting rings used to support the shield from the compressor pressure housing (left), and final flight cooler with four shields installed (right).

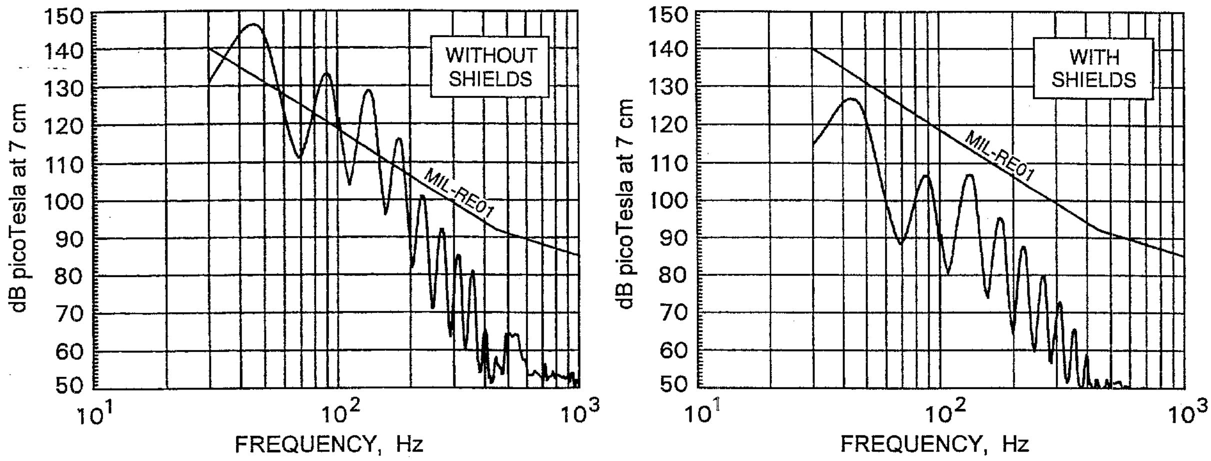


Figure 6. AC magnetic field emissions measured for the AIRS mechanical cooler with and without the addition of the flight mu-metal shields (versus MIL-STD 461C RE01 requirements).

high-permeability magnetic sheet material and stood off from each compressor end cap using structural aluminum rings as shown in the left-hand figure. The right-hand photograph in Fig. 5 shows the flight cooler system with the four shields installed.

Figure 6 highlights the measured AC magnetic field emissions from the completed AIRS cooler in contrast to measurements made before the shields were installed. With the shields, the cooler meets the MIL-STD-461C RE01 requirement on radiated magnetic field emissions.

Compressor DC Magnetic Field Emissions. In addition to generating AC magnetic fields associated with the AC coil currents, the compressor generates DC magnetic fields associated with the permanent magnets and iron pole pieces used to provide the magnetic circuit for the drive motors. The resultant DC magnetic dipole field falls off proportional to $1/R^3$ with increasing distance away from the cooler body. Figure 7 describes the DC magnetic field profile as measured for the AIRS compressor along the compressor centerline as a function of distance away from the compressor endcap (left figure), and along the length of the compressor at a 16-cm radial distance from the compressor centerline (right figure). Measurements were made using a Hall generator that was zeroed with the Earth's magnetic field so that the Earth's field contribution is not included in the measurements. Note that the lefthand graph of Fig. 7 presents data for the compressor both with and without the mu-metal shields shown in Fig. 5; it also shows the classic $1/R^3$ dependence of the magnetic field as a function of distance from the end of the compressor.

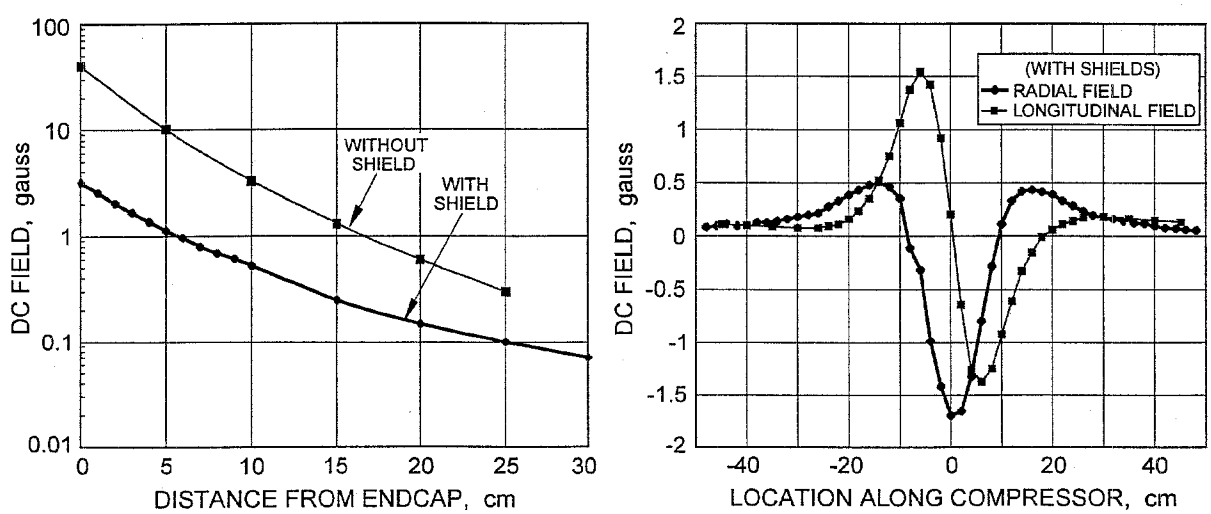


Figure 7. DC magnetic field emissions measured for the AIRS mechanical cooler.

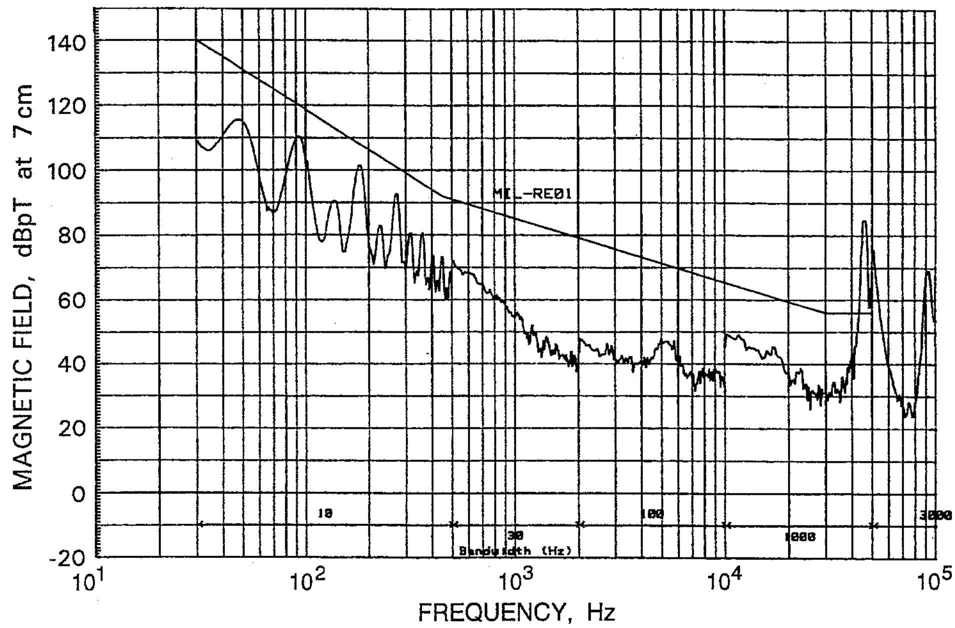


Figure 8. AC magnetic field emissions of the AIRS cryocooler electronics.

Electronics AC Magnetic Field Emissions. Although not a principal source of magnetic fields, the AIRS cooler electronics were also measured with respect to MIL-STD-462 RE01 and RE04 test methods. Figure 8 summarizes the RE01 performance of the electronics and highlights two magnetic field peaks associated with the 45 kHz PWM switching frequency.

Radiated Electric Field Emissions

As noted above, the AIRS cooler drive electronics utilize pulse-width-modulated power converters (PWMs) to synthesize the compressor drive waveform with maximum efficiency and low harmonic distortion. Early in the program it was recognized that the high internal currents associated with the 45 kHz PWM switching frequency are a major source of electric field emissions and must be carefully contained in an EMI-proof enclosure. To this end, the AIRS cryocooler electronics were packaged in an all-aluminum enclosure, shown in Fig. 9, with extensive internal compartmentalization and filtering of inter-compartment penetrations.

The radiated electric field emissions of the AIRS electronics were measured using MIL-STD-462 RE02 narrowband and broadband electric field emission specifications. Measurements were conducted at a distance of 1 meter from the geometric center of the electronics. Several antennas were used to measure the emissions up to a frequency of 10 GHz.

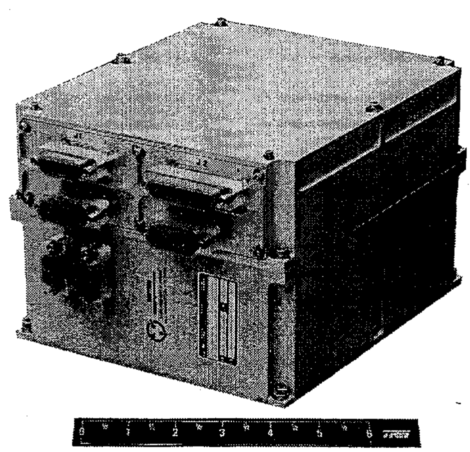


Figure 9. AIRS electronics in heavily EMI-shielded enclosure.

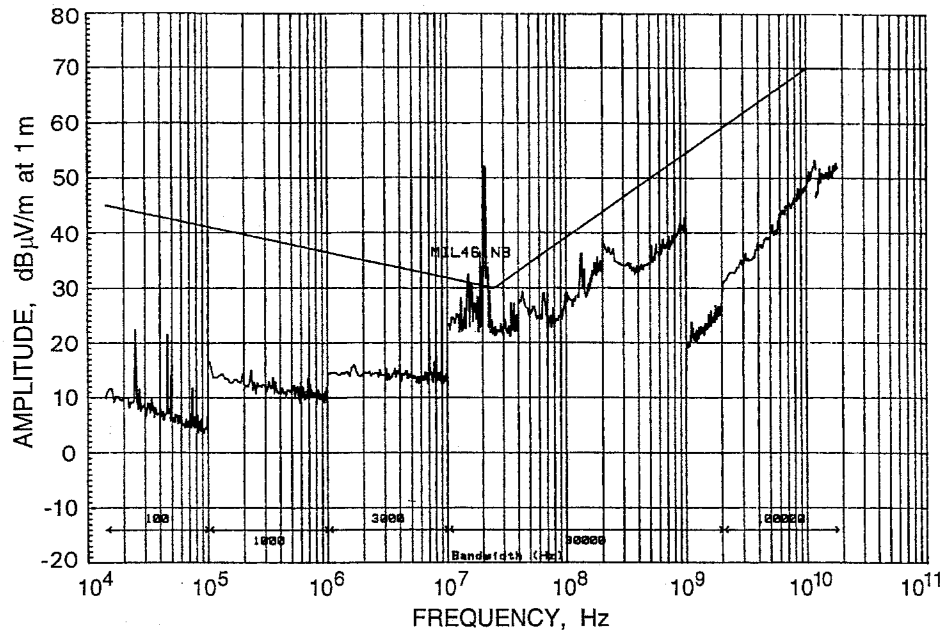


Figure 10. Electric field emissions of AIRS electronics.

Figure 10 shows the low radiated electric field emissions achieved with the AIRS electronics. Discontinuities in the data are changes in the antennas, amplifiers, and bandwidths used to cover the different frequency bands. The localized peak above the RE02 limit at 20 MHz is associated with the computer clock frequency and is due to inadequate shielding of a non-flight cable used for the testing.

Conducted Emissions on the 28 V Power Bus

In addition to generating large magnetic fields as noted above, the sinusoidal currents drawn by the linear motors at their 44.625 Hz drive frequency result in a large input ripple current at twice the drive frequency; this corresponds to full wave rectification of the drive current. The magnitude of the ripple current is inversely related to the operating DC voltage, and proportional to the operating power. It is difficult to significantly filter this primary ripple current because of its large magnitude and low frequency.

To help accommodate this large ripple current, the AIRS cryocoolers are supplied by a set of dedicated 28 Vdc "dirty bus" power circuits that allow an input ripple current as high as 200% p-p/average. In addition, the cooler power passes through the AIRS instrument where additional powerline filtering and inrush current suppression is accomplished.

The 28 Volt power lines of the AIRS cooler were tested for ripple current emissions in both the narrowband and broadband frequency spectrums. Measurements were conducted on both the high-side (positive) and return (negative) lines using a current probe. A line impedance simulation network was inserted in the 28 Volt line to closely simulate the spacecraft bus power impedance; the impedance, which is a function of frequency, is 0.25 ohms for frequencies below 1 kHz.

Figure 11 is the narrowband conducted emissions profile on the 28 Volt positive lead. The specification line is that of MIL-STD-461C CE01/03. The harmonics of the 44.625-Hz drive frequency are clearly observable, as are extensive harmonics of the 45 kHz pulse-width-modulated power converters. The return (negative) lead current emission profiles had nearly identical emission levels. The extensive over-spec peaks in the region from 90 kHz to 20 MHz are filtered out by the AIRS instrument power line filter, and are not allowed onto the spacecraft power bus.

Input Ripple Current Test Results (Time Domain). The time-domain waveform of the input ripple current was also measured for a range of electronics input power levels. Figure 12 presents example input-current waveforms, while Fig. 13 plots the measured relationship between ripple-current level and cooler input power. Note that the input ripple exceeds 200% at the

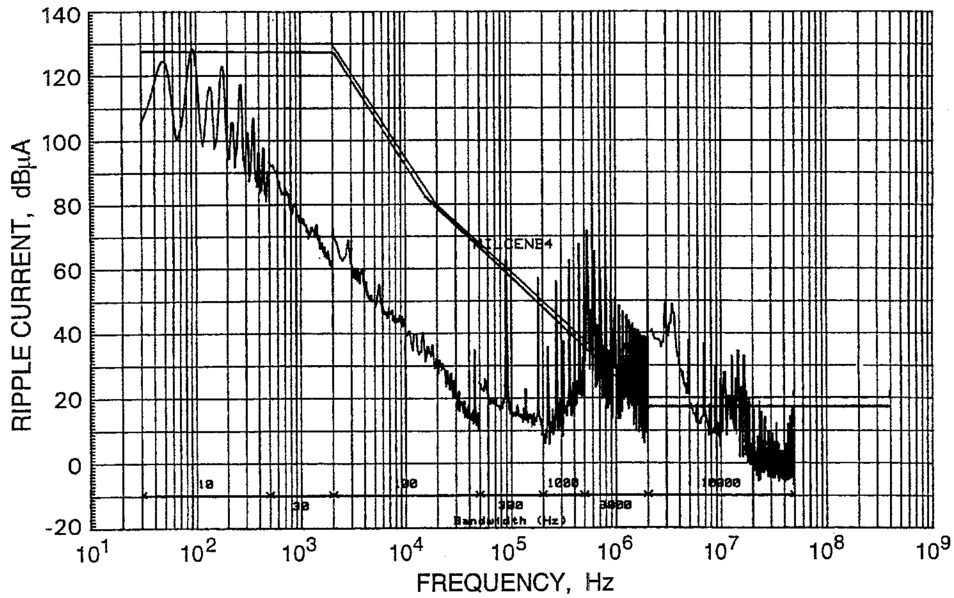


Figure 11. Conducted ripple-current emissions of AIRS electronics on 28 V power bus.

higher cooler power levels; this will be partially attenuated by the filtering accomplished at the instrument level. The high ripple current levels reflected onto the spacecraft bus by the AIRS cryocooler strongly support the decision to provide it with a separate "dirty" 28 V bus.

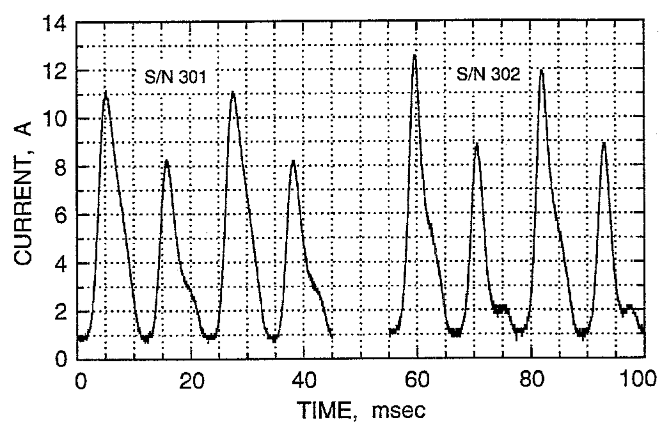


Figure 12. Comparison of the current waveforms on the 28 V power bus for the S/N 301 and 302 coolers, each with a system input power of 110 W.

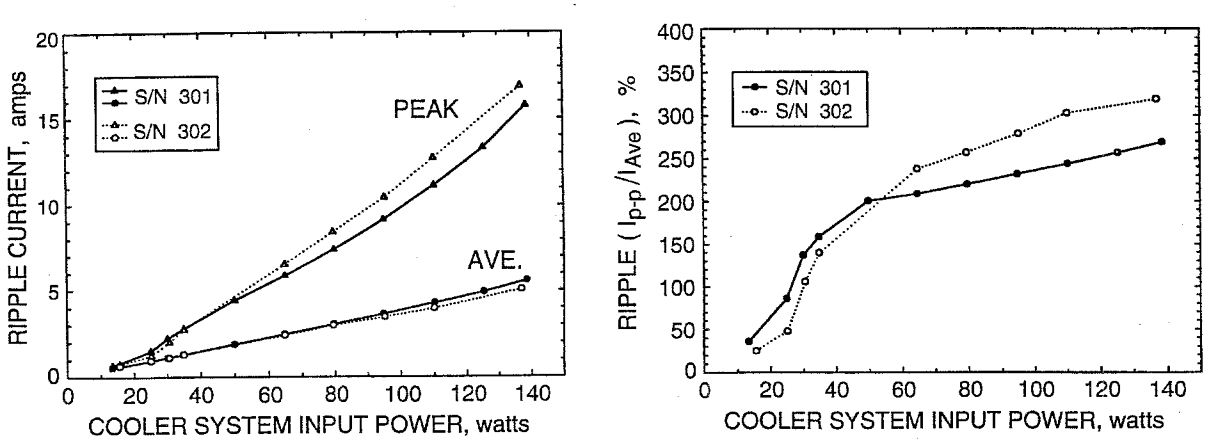


Figure 13. Relationship between ripple-current level and cryocooler input power level.

Power-On Inrush Current/Transient Voltage (Time Domain). The AIRS cryocooler flight electronics was tested for inrush current as well as transient voltage when the unit was switched from OFF to ON. A peak inrush current of approximately 9 amps was measured associated with charging of the internal circuitry; a voltage transient of -2 volts was recorded at the same time. It should be noted that the cooler has a slow start circuit upon powering of the compressor, so no further reflected voltage or current is observed at this point beyond the peak ripple current noted in Fig. 13.

AIRS CRYOCOOLER RADIATED AND CONDUCTED SUSCEPTIBILITY

The AIRS cryocooler and its electronics must not only produce low levels of EMI to be compatible with its surroundings, but must also withstand similar levels of EMI from external sources such as other spacecraft instruments. EMI susceptibility is also important because, in addition to voltage and current ripple on the power bus, the cooler power-ups can produce inrush current spikes that can draw down the voltage available to the operating cooler over short periods of time. The cooler and electronics must be able to maintain normal operation without malfunctioning under allowable levels of input voltage ripple and turn-on voltage transients.

The Electromagnetic Compatibility (EMC) tests were run on the AIRS cooler in three areas:

Susceptibility to Radiated Electric Field Emissions (14 kHz to 18 GHz). The AIRS cryocooler was subjected to AC electric fields according to MIL-STD-461C RS03. During operation, both the compressor and electronics were subjected to electric field strengths of 2 V/m from 14 kHz to 2 GHz, and then to a field strength of 10 V/m from 2 GHz to 18 GHz. No anomalies were observed.

Susceptibility to Radiated Magnetic Field Emissions (30 Hz to 200 kHz). The AC magnetic field susceptibility test involved exposure of the operating cooler to fields over a range of 30 Hz up to 200 kHz. The field strength level was 120 dBpT at the surface of the cryocooler. While being subjected to the AC magnetic fields, the cooler and electronics were constantly monitored for any anomalies. None were found.

Susceptibility to Conducted Emissions on the 28 Vdc Power Bus (30 Hz to 400 M Hz).

AC Voltage Ripple. The MIL-STD-461C CS01 requirement is ± 7 volts peak-to-peak from 30 Hz to 2 kHz. Before this level could be applied to the power bus, the peak current had reached 5 amps. While the cooler operation was being monitored, no change in the performance occurred. At 2 kHz, the injected voltage ripple was reduced (per specification) as frequency increased to 50 kHz, where it was then constant at 3 V p-p up to 400 MHz. The performance of the cooler was not affected.

Injected Voltage Transient. The requirement of method CS06 is that a transient voltage be injected on to the +28 Vdc line relative to chassis, on to the return line relative to chassis, and on to the +28 Vdc line relative to the return line. The transient is to have a 40 V peak amplitude, 10 μs duration, and be repeated at 60 pulses per second for 5 minutes. The test was conducted and no anomalies were observed in the cryocooler operation or performance.

SUMMARY AND CONCLUSIONS

The AIRS cryocooler EMI development and testing activity has been a highly collaborative effort involving cooler development at TRW, integration studies at LMIRIS, and magnetic shielding and acceptance testing activities at JPL. As one of the first cryocoolers to be required to meet stringent EMI constraints, the AIRS cooler offered an important opportunity to measure and understand the important EMI/EMC issues and parameters. Extensive development and test results have been presented including development of the magnetic shields to bring the AC magnetic fields of the AIRS cooler within the requirements of MIL-STD-461C, and data on the entire suite of EMI characteristics of the AIRS cooler with its flight electronics. Particular attention has been given to characterizing the levels of input ripple current to allow future applications to judge the ripple-current compatibility with specific power system capabilities and to serve as data for scoping the design of future ripple suppression hardware.

ACKNOWLEDGMENT

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, Lockheed Martin IR Imaging Systems, and TRW, Inc; it was sponsored by the NASA EOS AIRS Project through an agreement with the National Aeronautics and Space Administration.

REFERENCES

1. Ross, R.G., Jr., Johnson, D.L., Collins, S.A., Green K. and Wickman, H. "AIRS PFM Pulse Tube Cooler System-level Performance," *Cryocoolers 10,* Plenum Publishing Corp., New York, 1999.
2. Ross, R.G., Jr. and Green K., "AIRS Cryocooler System Design and Development," *Cryocoolers 9,* Plenum Publishing Corp., New York, 1997, pp. 885-894.
3. Chan, C.K., et al., "Performance of the AIRS Pulse Tube Engineering Model Cryocooler," *Cryocoolers 9,* Plenum Publishing Corp., New York, 1997 pp. 195-202.
4. Chan, C.K., et al., "AIRS Pulse Tube Cryocooler System," *Cryocoolers 9,* Plenum Publishing Corp., New York, 1997, pp. 895-903.
5. *Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference*, MIL-STD-461C, Department of Defense, Washington, DC (1986).
6. Johnson, D.L., et al., "Cryocooler Electromagnetic Compatibility," *Cryocoolers 8,* Plenum Publishing Corp., New York, 1995, pp. 209-220.
7. CONETIC AA alloy is manufactured by the Magnetic Shield Division, Perfection Mica Company, Bensenville, IL.
8. Moly Permalloy is manufactured by Allegheny Ludlum Steel Corp., Pittsburgh, PA.